COLORADO STATE UNIVERSITY – PUEBLO

Final Report

Developing Engineered Fuel (Briquettes) using Fly Ash from the Aquila Coal-fired Power Plant in Cañon City and locally available Biomass Waste

Grant No: DE-FG26-05NT4290
Period: 7-01-2005 to 6-30-2006

In partnership with

Aquila Power Plant, Canon City, CO
and
International Center for Appropriate and Sustainable Technology, Golden, CO

H. Carrasco and H. Sarper

Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Number DE-FC26-05NT42490."

Summary

The objective of this research is to explore the feasibility of producing engineered fuels from a combination of renewable and non renewable energy sources. The components are flyash (containing coal fines) and locally available biomass waste. The constraints were such that no other binder additives were to be added. Listed below are the main accomplishments of the project:

1. Determination of the carbon content of the flyash sample from the Aquila plant. It was found to be around 43%.
2. Experiments were carried out using a model which simulates the press process of a wood pellet machine, i.e. a bench press machine with a close chamber, to find out the ideal ratio of wood and fly ash to be mixed to get the desired briquette. The ideal ratio was found to have 60% wood and 40% flyash.
3. The moisture content required to produce the briquettes was found to be anything below 5.8%.
4. The most suitable pressure required to extract the lignin form the wood and cause the binding of the mixture was determined to be 3000psi. At this pressure, the briquettes withstood an average of 150psi on its lateral side.
5. An energy content analysis was performed and the BTU content was determined to be approximately 8912 BTU/lb.
6. The environmental analysis was carried out and no abnormalities were noted.
7. Industrial visits were made to pellet manufacturing plants to investigate the most suitable manufacturing process for the briquettes.
8. A simulation model of extrusion process was developed to explore the possibility of using a cattle feed plant operating on extrusion process to produce briquettes.
9. Attempt to produce 2 tons of briquettes was not successful. The research team conducted a trial production run at a Feed Mill in La Junta, CO to produce two (2) tons of briquettes using the extrusion process in place. The goal was to, immediately after producing the briquettes; send them through Aquila's current system to test the ability of the briquettes to flow through the system without requiring any equipment or process changes.
10. Although the above attempt failed, the plant is still interested in producing briquettes.
11. An economic analysis of investing in a production facility manufacturing such briquettes was conducted to determine the economic viability of the project. Such a project is estimated to have an internal rate of return of 14% and net present value of about $400,000.
12. An engineering independent study class (4 students) is now working on selecting a site near the power plant and determining the layout of the future plant that will produce briquettes.

Papers Published:

A thesis entitled "Supplemental Fuel Production Using Fly ash and Biomass Waste" was completed by S. M. Dede and accepted by the university on 9/18/2006.

Table of Contents

Chapter 1

Introduction

On September 6, 2005, the Aquila team was officially formed to research the feasibility of manufacturing engineered briquettes from wood and fly ash on a commercial basis for the Aquila Coal Plant in Cañon City. The objectives of this research were as follows:

1. Produce wood/fly ash briquettes with a 50% to 66.67% wood waste content using no binders to evaluate the technical viability of producing large quantities of briquettes consistently from fly ash and sawdust.
2. Test the ability of two tons of briquettes produced to flow through Aquila's current system without requiring any equipment or process changes.
3. Conduct an economic analysis of a production facility manufacturing such briquettes.
4. Determine the amount of pollution prevention such an operation can achieve.
5. Determine the precise energy impact (energy consumed to produce the briquettes versus the energy content of the briquettes produced).
6. Evaluate any other benefits of such an undertaking.

The optimal solution was required to fulfill the list of the constraints below:

1. Avoid air re-permitting: The process must avoid burning anything other than coal and wood products to avoid significant re-permitting.

2. Avoid fuel-handling re-permitting: The process must use the current furnaces without changing the way Aquila currently handles the fuel.

3. Demand: The process must produce a product that is in demand or desired by a second party as a commodity.

The W. N. Clark Power Plant

The W. N. Clark Power Plant is located in Canon City and is approximately thirty-six miles west of Pueblo City and forty-five miles south west of Colorado Springs.

The power plant is located on the western edge of the city, and lies between the Arkansas River and the federal Administrative Maximum Penitentiary, dubbed "Super Max" (Figure 1.1).[1]

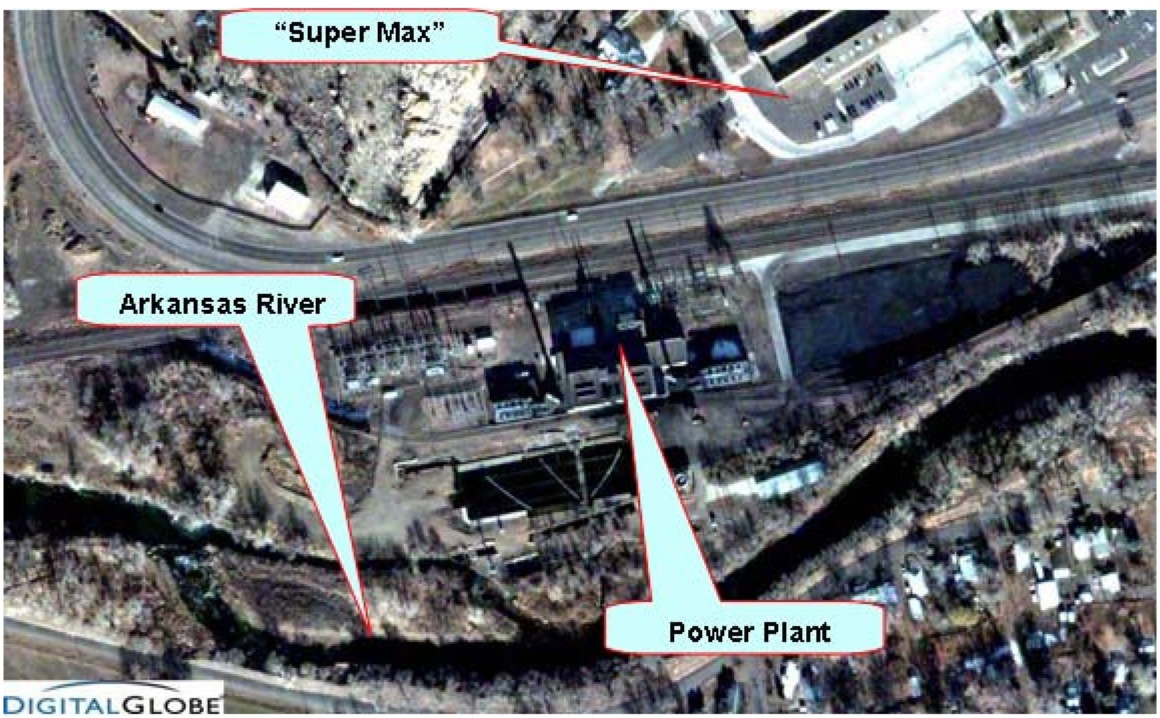

Figure 1.1: Aerial view of power plant and surrounding area (Digital Globe).

[1] Alternatives Assessment to Determine Effective Re-use of Fly ash, Bottom Ash and Coal Dust From Canon City Power Plant, CABJ Engineering Consultants, 2004.

Figure 1.2: The WN Clark Power Plant[1]

The plant which started in 1955 has two coal-fired B&W stoker fired boilers which have a joint maximum capacity of 43 Mega watts per hour, burn approximately 400-500 tons of unwashed coal per day and generate over 65 tons per day of fly ash and bottom ash, which are discarded as waste products in the local landfill. Details of the boilers are as follows:

1. *Unit 1: On-line in 1955. Steam flow 150,000#/hr at 975 psi, 915 F. Generator is rated at 16 MW/HR and operated at 17.6 MW/HR. Capacity factor YTD through August is 66.86% based on 17.6 MW/HR. The coal flow rate is approx. 8 tons/hr.*
2. *Unit 2: On-line 1959. Steam flow 210,000#/hr at 1,000 psi and 910 F. Generator is rated at 22.5 MW/HR and operated at 24.9 MW/HR. Capacity factor YTD through August is 77.71% based on 24.9 MW/HR. Coal flow rate is approx. 12 tons/hr.*

Within each boiler, air is forced from under the conveyers to burn the coal. This forced air blows the fly ash along with approx. 40% coal dust into the flue chamber where it can be collected. The coals after they are burned at the end of the conveyor are collected as bottom ash. Fly ash is captured in the hoppers below the bag-house cells continuously utilizing a reverse airflow system. The ash is transported by a dry vacuum system to the ash silo twice/day. Bottom ash collects in the bottom ash hoppers below the furnace floor continuously and is transported by the dry vacuum system to the same ash silo as the fly ash twice/day. The mixed product is loaded into a contractor's truck and disposed of daily.[2] *The fly ash has coal dust incorporated in it and the power plant ultimately would like to re-burn this waste product and regain the lost energy*.[1]

The estimated mix is 65% fly ash and 35% bottom ash. Coal is delivered by railcars directly into the facility. The approximate delivery cost is $32.00/ton. The W. N. Clark Power Plant is also capable of co-firing coal with wood. The biomass is being co-fired with coal in the existing stoker system.[3] The Power Plant is permitted to co-fire up to 5% wood by weight (i.e. 20 – 25 tons of wood per day). Prior efforts were discontinued initially because of inconsistent wood supply and quality issues with the size of wood particles provided. Currently it co-fires wood of suitable sizes (small wood chips) though on a small scale only and they are a by-product of forest fire mitigation activities. [3]

[2] Aquila Narrative, Colorado State University-Pueblo, 2005.

[3] http://www.state.co.us/oemc/programs/waste/forest_thinnings/canoncity.htm

Coal Fly Ash

Coal fly ash is produced from the burning of pulverized coal in a coal-fired boiler. It is a fine-grained, powdery particulate material that is carried off in the flue gas and usually collected from the flue gas by means of electrostatic precipitators, bag houses, or mechanical collection devices such as cyclones.[1] The amount of unburned carbon in the fly ash varies from plant to plant but is usually within 20- 45 % of fly ash

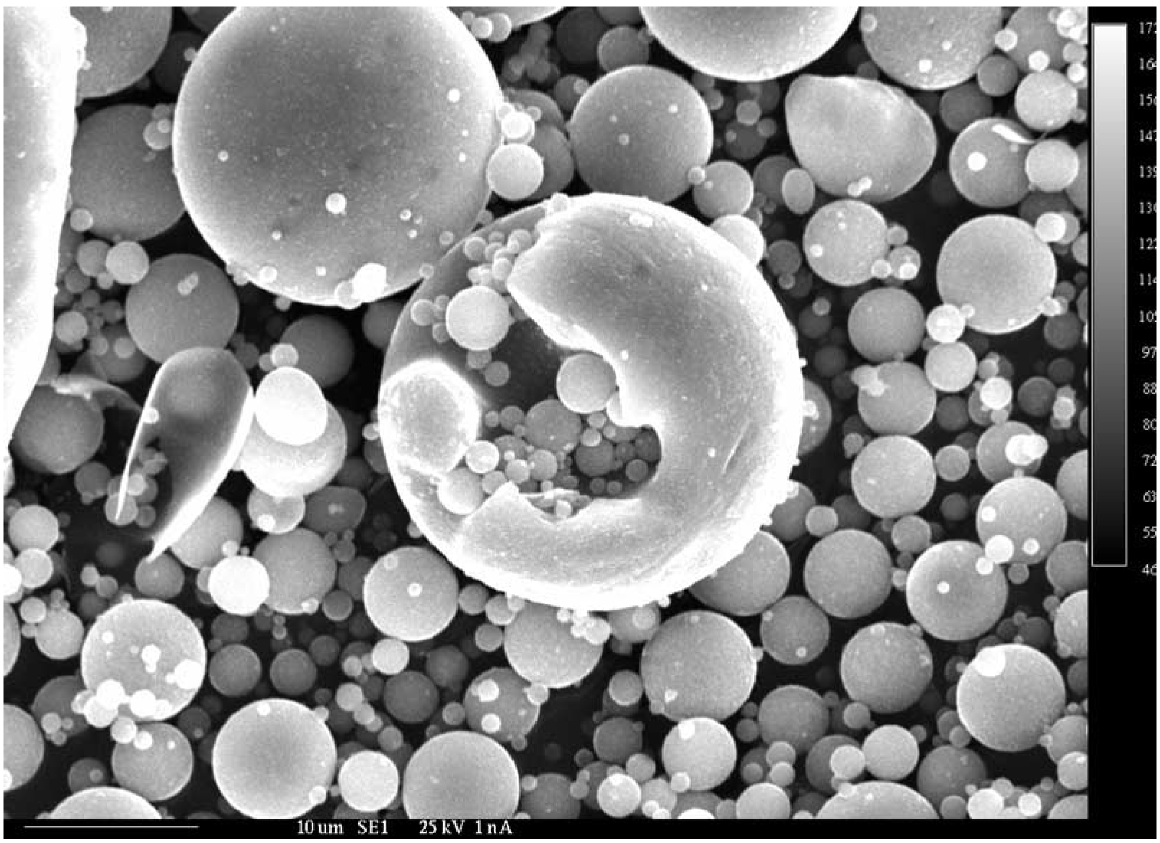

Figure 1.3 Fly ash from a coal fired power plant[4]

[4] http://geoinfo.nmt.edu/labs/microprobe/description/sem.html

Figure 1.4: Fly ash Sample from the WN Clark Power Plant

Fly ash consists mainly of fine glassy- spherical particles that are amorphous (glassy) in nature and either hollow or solid. The particle size distribution of most bituminous coal fly ashes is usually less than 0.076mm. The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area (measured by the Blaine air permeability method) may range from 170 to 1000 m2/kg.[1]Their color varies from tan to gray to black depending on the carbon content of the fly ash: The more the carbon content, the darker the color of the fly ash. The principal components of fly ash are Carbon, Iron oxide, Calcium, Calcium oxide, Magnesium oxide, Alumina and Silica. They vary in their content from fly ash to fly ash depending on the Class of Coal.

Biomass Waste

Forest fire mitigation activity in the form of forest thinning occurs often in the forest area around Canon City. This is because the area around Canon City has large tracts of forest mostly from Ponderosa Pine that are overstocked and therefore in danger of burning and being infested with beetle. The area includes federal (USFS & BLM), Fremont County and Canon City Parks plus private landowners. The by-product of forest thinning mostly results in piles of slash, burn and small wood chips that are generally sent to the landfill or burned in a place as a disposal method. The energy content of the biomass was found to range from 4500 to 6000 BTU's per lb depending on the moisture content which can range from 20 to 100%. Current approximations of the amount of thinning and pruning waste sent to the local landfill are estimated at 15-20 tons per day. In addition to the above-mentioned sources of woody biomass waste, the two local sawmills generate over 35 tons of process waste (chips, bark and sawdust) that go to the local landfill.

Figure 1.5: Ponderosa Pine[5]

[5] http://oregonstate.edu/trees/con/spp/pinespp.html

The Ponderosa Pine is one of America's abundant tree species, covering approximately 27 million acres of land.[6] The Ponderosa Pine wood is a relatively large tree averaging 48" in diameter and 130 feet in height, and belongs to the deciduous species of woods. It has a pale yellow color that varies from deep yellow to reddish brown. All wood used in this project is biomass waste from Ponderosa Pine wood.

Lignin

Lignin is the second most abundant organic material on earth. It is a chemical compound found in abundance in renewable sources such as trees and agricultural plants. *Lignin is the irreversible removal of water from sugars, creating aromatic compounds through the phenylpropanoid pathway. Lignin polymers are cross-connected structures with molecular weights on the order of 10,000 amu*.[7]It forms an integral part of the cell walls of cells such as sclereids, xylary fibers and tracheids, resulting in the strength of wood and constitutes about one- third of the mass of dry wood. It is a very complex natural polymer with many random couplings so the exact chemical structure is not known.[8]

[6] http://www.wwpa.org/ppine.htm
[7] http://www.biocrawler.com/encyclopedia/Lignin
[8] http://www.lignin.org/

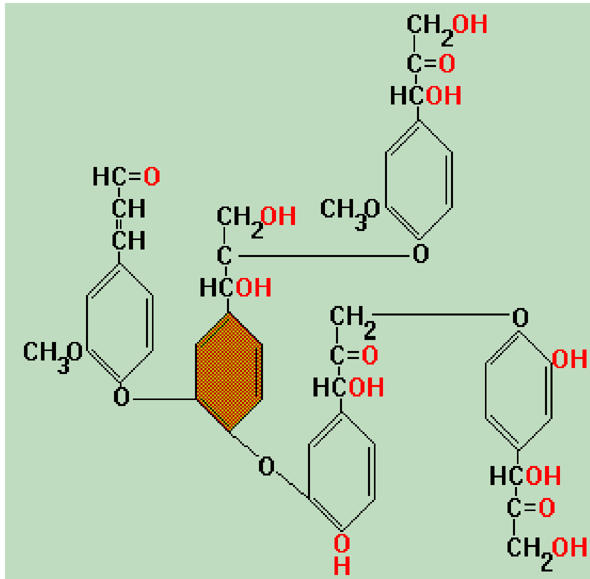

Figure 1.6: An early stage in the condensation of various monomers to form lignin

When an OH reacts with another, an ether linkage is formed. As we have seen, an OH reacts with an aldehyde to form a hemiacetal. The reaction of OH groups with ketones forms ketals. There are several groups shown in red that can react further. Some will simply extend the polymer while others would establish cross linking. The monomer that is shaded in orange has three of its functional groups linked to other monomers, so it is starting a branch or cross link. The large lignin molecules fill three dimensions and are heavily cross linked[9].

Lignin has several uses but is mostly known to be a very effective and economical adhesive that can be used for several binding purposes: binder in particleboard, adhesive for linoleum, raw material for processing into chemicals and animal feed pellets.

[9] http://www.rpi.edu/dept/chem-eng/Biotech-Environ/FUNDAMNT/lignin.htm

Chapter 2

Prefatory Research

The purpose of the first set of experiments was to obtain good knowledge and confirm the properties of the materials we were to work with. Production of briquettes involved working with fly ash and wood biomass waste. The various parameters such as the carbon content, energy content and moisture content had to be studied to help us in building an effective product. More over the processes we examined to produce briquettes were similar to wood pellet operation so we visited La-Junta Saw Mill, La-Junta, Rocky Mountain Forest products, Laramie ,Wyoming, the Aquila Coal-fire plant in Canon city, and Tom Mc Comb Lumber Company, Canon city to get a clear picture of the wood pellet process.

Energy Analysis

The energy value of a fuel, or the fuel content, is the amount of potential energy in the fuel that can be converted into actual heating ability. The value is determined by the chemical composition of the fuel and can be calculated and compared with different grades of fuel or even other materials. Materials of different grades do produce differing amounts of heat for a given mass.

While chemistry provides methods of calculating the heating value of a certain amount of a substance, there is a difference between the theoretical value and the actual value.

The following techniques could be used to determine the energy content in fuel: proximate analysis and gross calorific value analysis. We used gross calorific value. The gross calorific value Q is the number of heat units (BTU) liberated when fuel is completely combusted with oxygen under standard conditions. This heat value will include water vapors and other compounds (acid forming gases) which normally escape to the atmosphere when combusted. Q is a complex function of the elemental composition of the fuel. Q can be determined experimentally using bomb calorimeters. This was based on the fact that hydrocarbons react easily with oxygen. The bomb calorimeter is an adiabatic apparatus used for measuring the heat generated by a chemical reaction, change of state, or formation of a solution. It is a constant-volume calorimeter that is capable of withstanding force of explosive reactions and high pressures. The enthalpy change, H, for this process is related to the internal energy, and pV, as follows:

$$\Delta H^o = \Delta U + \Delta (pV) \qquad \text{(Eq. 1)}$$

$$\Delta (pV) = \Delta nRT \qquad \text{(Eq. 2)}$$

The procedure required combusting benzoic acid first to calibrate the bomb calorimeter. After that, a solid sample weighing about 1g is put in a stainless steel bomb and pressurized with oxygen to 20atm. The bomb is placed in a metal bucket containing two liters of water. A thermometer to measure temperature change and a stirrer to ensure uniform temperature are placed in the bucket and sealed tightly in an insulating vessel. When the sample is ignited, the bomb temperature increases and subsequently increases the temperatures of the water and the bucket until all are at the same temperature. The temperature usually reaches a maximum, and then a negative sloping line is observed in the time versus temperature graph.

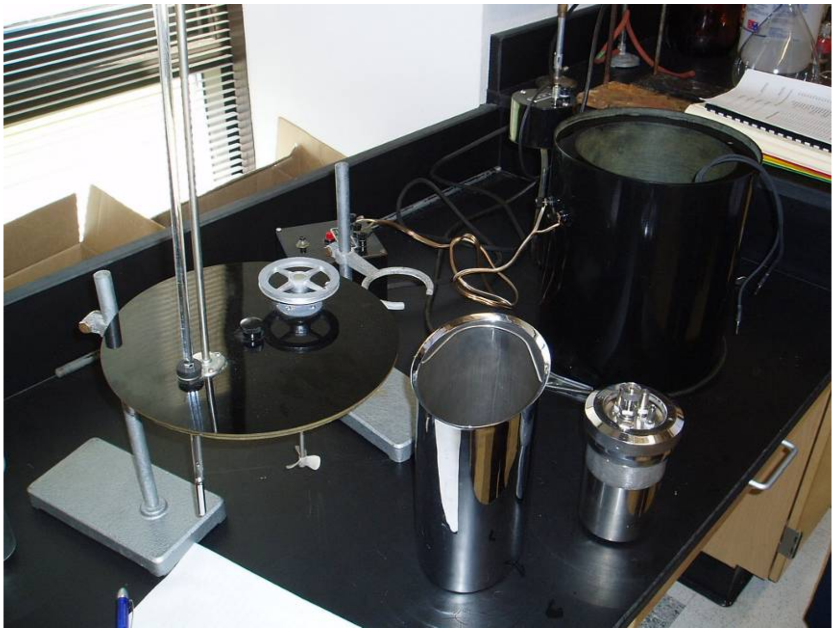

Figure 2.1: Bomb Calorimeter to determine energy content of fuel

When the experiments were conducted we were able to determine the calorific value of the benzoic acid which we used to calibrate the bomb calorimeter. Later the actual sample was used and result of the experiment (Figure 2.2) showed a combustibility problem. This was also confirmed with the presence of unburned wires on the electrodes and the fact that the Bomb Calorimeter thermometer showed no rise in temperature.

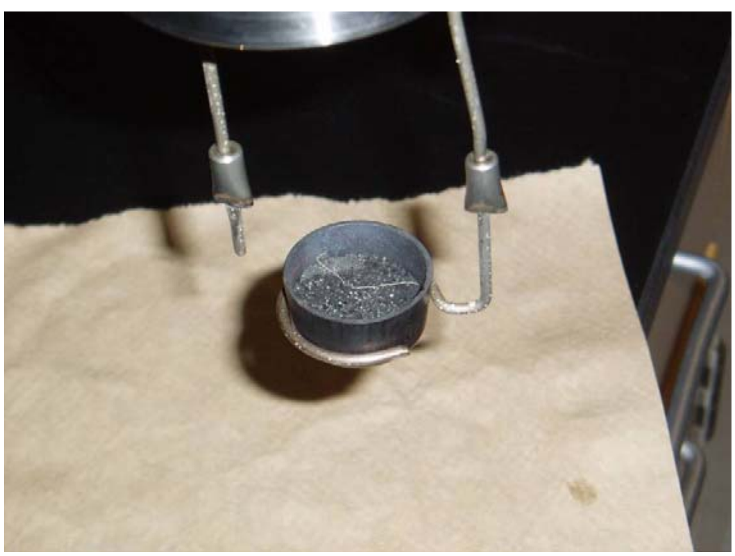

Figure 2.2: Unburnt wires in Bomb Calorimeter showing combustion problem

Carbon Content Analysis

The fixed carbon content of the fuel is measured by the loss in weight of the fuel when subjected to combustion under standard conditions. Fixed carbon is used as an estimate of the amount of coke that will be yielded from a sample of fuel. It is based on the fact that since carbon in its fossil form is combustible, provided no smoke occurs, only carbon would combust. The process requires the subjection of a sample in a crucible to high heat through the use of a meeker burner that burns at approximately 500C.

The equation for this reaction is

$C_xH_yO_z$ + (X+Y/4-Z/2) O_2(g) ------> X CO_2(g) + (Y/2) H_2O(g)[10]

A sample of fly ash weighing 0.600g was heated for 40minutes (Figure 2.3), left to cool for 5 minutes and weighed (Figure 2.4). This process was carried out again to ensure that a constant mass was reached indicating that all combustible carbon had burnt. In all of this, no smoke was observed.

Figure 2.3: Experimental setup to determine carbon content of the fuel

[10] http://thunder1.cudenver.edu/chemistry/classes/LabNet/bomb/theory.html

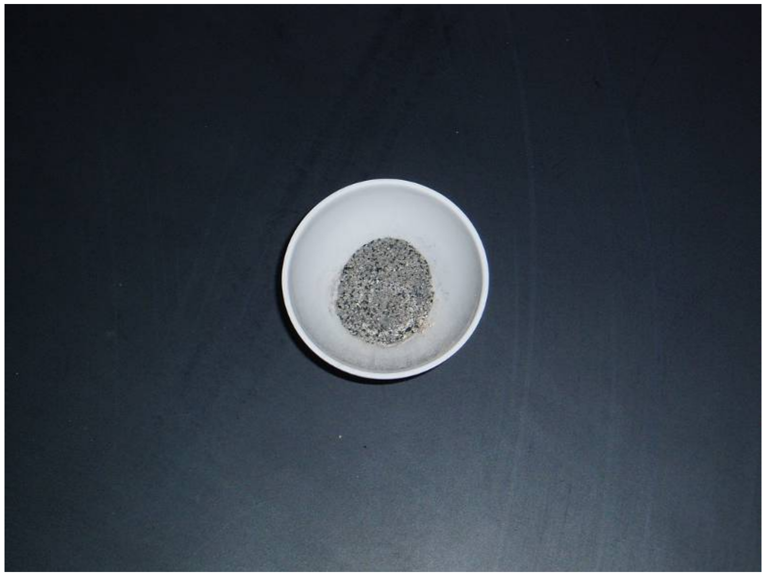

Figure 2.4: Fly ash Fuel sample after the experiments

It is very much evident from the experiments that there was a significant color change in the sample of the fuel. The fuel lost all its color as a result of the heating, the supply of the heat by the Bunsen burner. The table shows the analysis done to calculate the carbon content in the fuel.

Table 2.1The result is shown in the table below

	Sample weight before Combustion	Sample weight after Combustion
First Experiment	0.600g	0.3419g
Second Experiment	0.3419g	0.3416g

There was a 43% loss in weight. This implied that the fly ash sample contained 43% of carbon.

Moisture analysis

Moisture is an important property of fly ash, as all coals are mined wet. Groundwater and other extraneous moisture are known as adventitious moisture and are readily evaporated.

Moisture held within the fly ash itself is known as inherent moisture and is analyzed. Moisture may occur in four possible forms within fly ash:

- Surface moisture: water held on the surface of coal particles
- Hygroscopic moisture: water held by capillary action within the micro fractures of the fly ash
- Decomposition moisture: water held within the fly ash's decomposed organic compounds
- Mineral moisture: water which comprises part of the crystal structure of hydrous silicates such as clays

We used a moisture meter (Delmhorst®, BD-2100) to determine the moisture content of our samples. The fly ash samples showed moisture content below 5.8% when measured (this was the lower limit of the moisture measuring device). Further experiments confirmed a zero percent moisture content as no change in mass was observed after 300g of the sample was heated in an oven at 80 ^{0}C for 27 hrs 30 minutes.

Experiments were also carried out to confirm the significance of moisture content in the wood by spraying the wood/fly ash mixture with some steam. This yielded products that crumbled immediately. We implied from this experiment that moisture content could not be taken for granted. So the team heated 656.3g of wood in an oven at 80 ^{0}C for 27 hrs 30 minutes. A weight loss of 371.5g was observed indicating a 56% loss in moisture content. When measured with the moisture meter, the moisture content was found to be below 5.8%. Briquettes produced at this moisture content produced excellent results. Although other ranges such as 6-8%, 8-10%, 10-12% and 12-15% were explored to determine the best moisture content for the briquettes, they all produced unsatisfactory results. So the optimal moisture content which was used was moisture content below 5.8%.

Industrial visit

We carried out three plant visit to the following organization to get carry out preliminary research about this project. The organizations we visited are as follows

1. Aquila Power Plant ,Canon City, Colorado
2. Rocky Mountain Forest products, Laramie ,Wyoming
3. La-Junta Cattle Feed manufacturing plant, La Junta ,Colorado
4. Tom McComb Lumber Company, Canon City, Colorado

Aquila Power Plant

The visit to Aquila power plant was a great learning experience and gave us more insight into the energy production process using coal, and how the fly ash used for producing the briquettes are produced as well. Discussions with staff of Aquila gave us information on the fuel requirements of Aquila, and dimensions of the briquettes to be developed. As a result of the kind of feeding mechanism and crusher used in Aquila, the briquettes were to be no more than an inch in diameter and length. This would result in Aquila not requiring use of the crusher to further crush the fuel and would lead to energy savings as well.

Rocky Mountain Forest Products

Rocky Mountain Forest Products was a Wood Pellet manufacturing plant based in Wyoming. The visit to that plant gave us great information on modern wood pellet manufacturing operations.

Chapter 3

Briquetting Technologies

Closed Chamber Press

The closed chamber compression press process was relatively simple. Sawdust with a proper moisture ratio below 5.8% (typically as low as possible) mixed with fly ash at a fixed ratio 60:40 respectively was pressed in the closed chamber of a die under high pressure. The result was a briquette formed from the mixture. The aim was to produce cylindrical briquettes one inch in height and diameter.

We used a manual hydraulic press to obtain the high pressure of 3000 psi. The prototype production steps are straightforward:

1. Dry the sawdust (in a suitable oven) until its moisture ratio is below 5.8 %
2. Weigh and mix dry sawdust and fly ash in the required (60:40) ratio.
3. Put the removable blocker disc under the die and fill the chamber with the mixture.
4. Put the metal punch on the chamber and place everything under the manual press
5. Apply pressure until you reach 3000 psi
6. Release the pressure and remove the blocker disc.
7. Push the metal punch a little bit more so that the briquette in the chamber pops out from the bottom

Below are a schematic diagram and pictures of the parts that were designed and produced in the machine shop for this process.

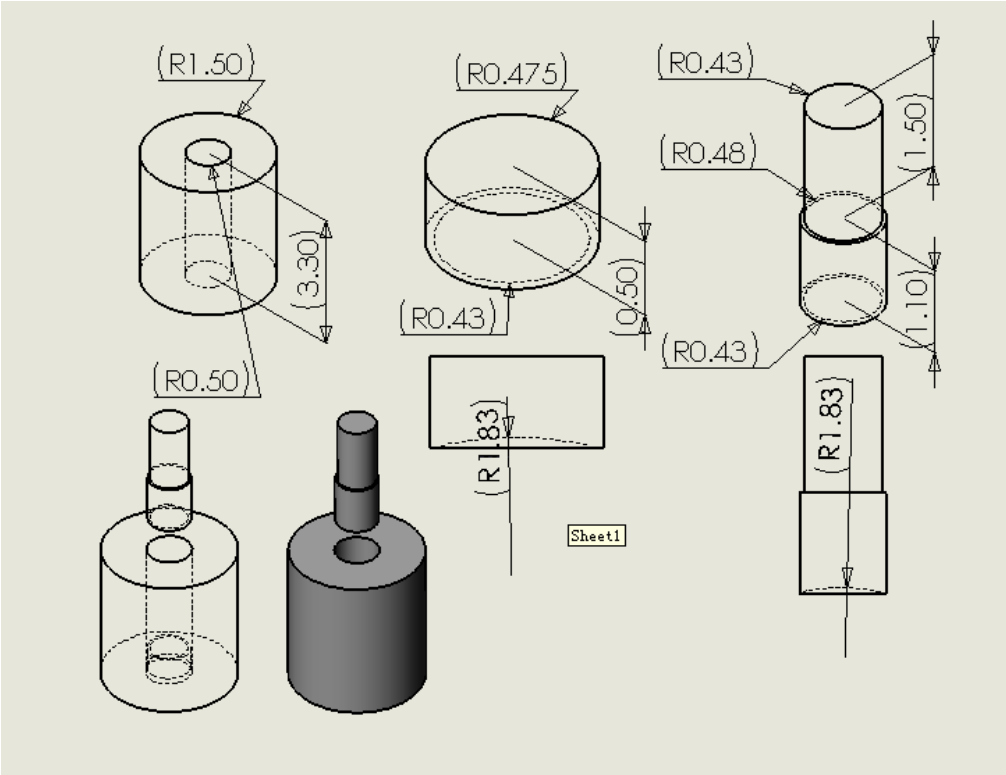

Figure 3.1 Schematic Drawing of Closed Chamber Model

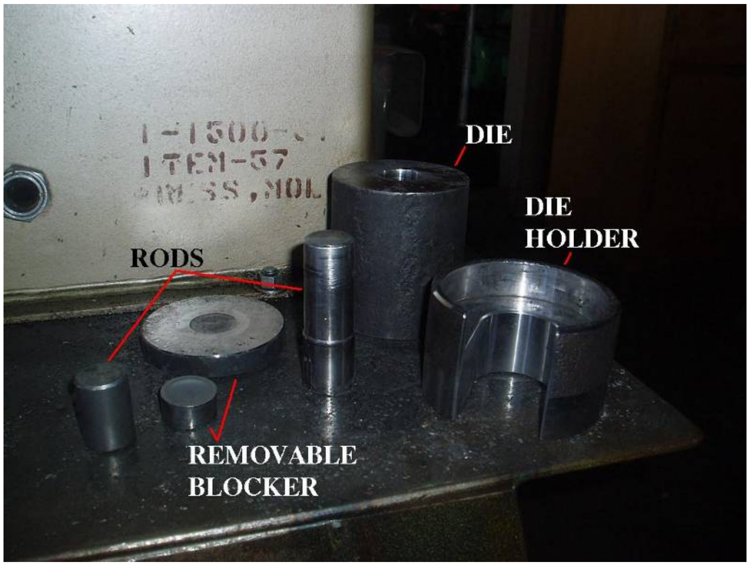

Figure 3.2 Whole Set of Parts

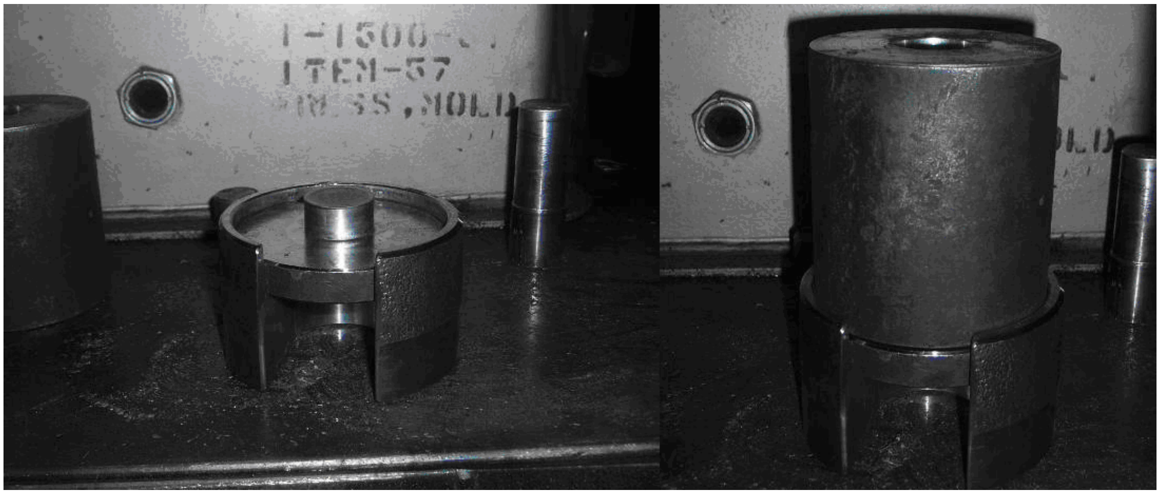

Figure 3.3 Removable blocker Combined with Die Holder

Removable blocker and then die is placed on top of die holder, as shown above. Then the chamber (the cylindrical hole in the die) is filled with the mixture from the top.

Figure 3.4 Closed Chamber Model

Then the bigger metal rod is placed on the hole of the die, and everything is placed under the manual hydraulic press. After applying 3000 psi, pressure is released and the removable blocker between the die and the die holder is removed. Pushing the metal rod little bit more (with the help of the short metal rod if necessary) will pop out the briquette in the chamber from the bottom hole of the die.

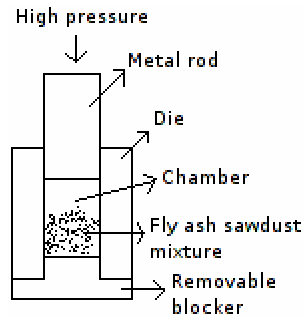

Figure 3.5 Schematic Drawing for Press Procedure

This is a very slow way of producing prototypes. One briquette which weighs about 11 grams takes approximately 4 minutes to produce since it is quite difficult to use the manual press. One idea is to parallelize the above process. An automatic press applies pressure on, say, seven dies placed in parallel.

Results of Closed Chamber Model

Three tests were conducted initially at 1500, 2000, and 3000 psi for ratios 50:50 and 60:40 respectively of wood and flyash. The wood to fly ash ratio of 60:40 (Figure 3.6) held together better than the 50:50 ratio (Figure 3.7) at each of the different pressures when a strength test was conducted on them all. The strength test was done by dropping a typical sample from a height of 60cm several times. The force experienced by the briquettes when dropped at this height was calculated to be F= mg = 9.5 * 9.8 = 0.0931N

It was observed that samples produced at 3000psi were stronger as they broke at the third trial while samples produced at 2000psi broke by the second trial. This was not surprising as it is expected that increased density would lead to increased compactness, strength and wear resistance.

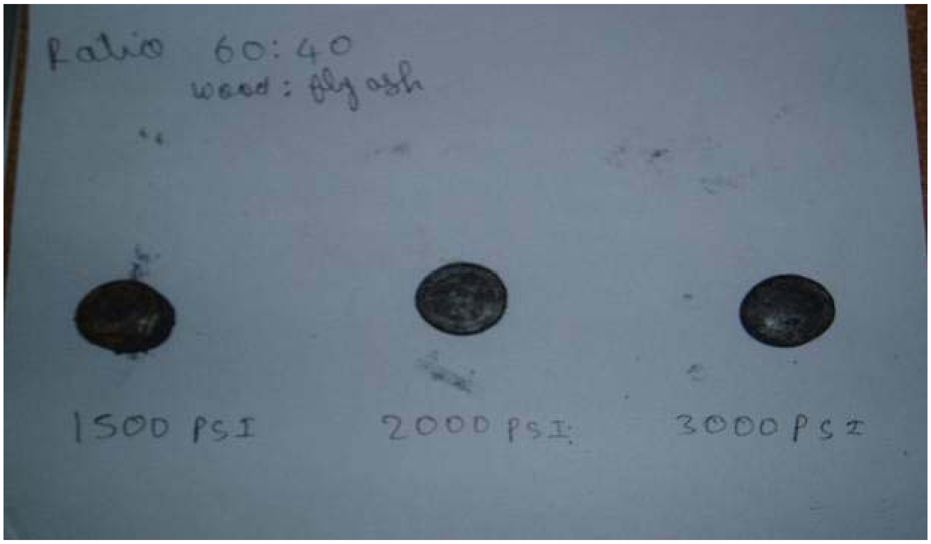

Figure 3.6 Briquettes with wood to fly ash ratio of 60:40

Figure 3.7 Briquettes with wood to fly ash ratio of 50:50

One challenge with the initial results was the difficulty in achieving a homogeneous because the wood chips were quite large compared to sawdust. We confirmed that the finess of the wood was an important factor to be considered for a successful product to be actualized because the finer the wood is, the more homogeneous a mixture is. Therefore a smaller screen (3/4 inch) from Crary Bear Manufacturing Company was purchased for the Hammer mill to be used in grinding the wood into finer particles. Subsequently, 200g of briquettes at 3000 psi were produced (Figure 3.8) and sent to Aquila for laboratory analysis.

Figure 3.8 Briquettes Produced at 3000 psi with Wood to Fly Ash Ratio of 60:40

On receiving the laboratory results of the first test, a decision was made to send another batch based on the second mixture for lab tests in order to confirm the impressive results obtained. Results from both laboratory tests are tabulated below:

Table 3.1 Analysis Results From Aquila Lab

	First Result		Second Result	
	As Received	**Dry**	**As Received**	**Dry**
Total Moisture	1.52		2.04	
Ash	29.02	29.47	22.17	22.63
Sulphur	0.3	0.31	0.16	0.16
Gross Calorific Value	8372	8601	8309	8482
Carbon	55.47	56.33	53.2	54.31
Hydrogen	1.63	1.66	0.27	0.28
Nitrogen	0.67	0.66	0.67	0.68
Oxygen	11.37	11.66	21.5	21.94
Fluorine ug/g		98		
Chlorine	<0.01	<0.01		
Mecury, ug/g		0.31		0.26

The results reported very high BTUs that were above 8300 per pound in each case. The composition of pollutants was very minimal as well. We were also informed that a strength analysis was done on the briquettes by the Aquila team and the results were very satisfactory.

Failure compression tests of briquettes:

A more precise failure compression test was conducted to determine the strength of the briquettes. This is because the briquettes should be able to withstand some amount of force when sent in through the storage vessel and when flipped into the furnace. Failure compression test is a method for determining behavior of materials under crushing loads. Basically, the compression test is the opposite of the tension test with respect to the direction of loading. In compression testing the sample is squeezed and the load at failure is recorded. Ultimate compressive strength is the stress required for a specimen to rupture. This value is much harder to determine for a compression test than it is for a tensile test since the briquettes does not exhibit rapid fracture in compression. However, the team used this method because it was the only equipment available. Forty briquettes were produced and tested. The analyzed results were interpreted below using Minitab:

Table 3.2 Strength Test Results for Closed Chamber Model

Height(cm)	Mass(g)	Pressure(N)	Density(g/cm^3)
2.75336	14.4	394.27	1.03201
2.72288	14.1	388.93	1.02183
2.8321	15.1	406.285	1.05209
2.8067	14.5	388.04	1.01943
2.74828	14.4	424.085	1.03392
2.72542	13.6	349.77	0.98467
2.62636	13.5	371.13	1.0143
2.86258	15	357.78	1.034
2.84988	14.3	398.72	0.99014
2.794	15	362.23	1.05938
2.87528	15.1	447.67	1.03629
2.5146	12.2	332.86	0.95736

	2.59334	13	354.22	0.98917
	2.64668	13.8	377.36	1.02888
	2.8194	14.7	406.285	1.02884
	2.68732	13.6	351.105	0.99863
	2.5908	13.3	341.76	1.01299
	2.70002	13.9	376.47	1.01586
	2.79908	14.4	363.565	1.01516
	2.54	13.2	358.67	1.02548
	2.76352	13.7	216.618	0.97824
	2.86004	13.8	202.829	0.95212
	2.84226	14.1	242.416	0.97891
	2.89306	14.1	251.312	0.96172
	2.54	13.8	239.747	1.07209
	2.7432	13.3	221.51	0.95671
	2.89052	14.3	225.514	0.97622
	2.81432	13.4	199.27	0.93955
	2.86512	14.3	252.202	0.98487
	2.8575	13.8	238.858	0.95297
	2.5654	13.5	406.102	1.0384
	2.53238	11.6	306.467	0.90389
	2.3495	12	296.682	1.00784
	2.35712	12	361.622	1.00458
	2.42824	12.2	310.026	0.99141
	2.42316	12.7	330.486	1.03421
	2.30378	11.5	310.47	0.98502
	2.54254	13	339.827	1.00893
	2.27838	11.3	266.88	0.97868
	2.413	12.6	389.2	1.03039
Minimum	2.27838	11.3	199.27	0.90389
Maximum	2.89306	15.1	447.67	1.07209
Average	2.668778	13.5525	328.9811	1.00218

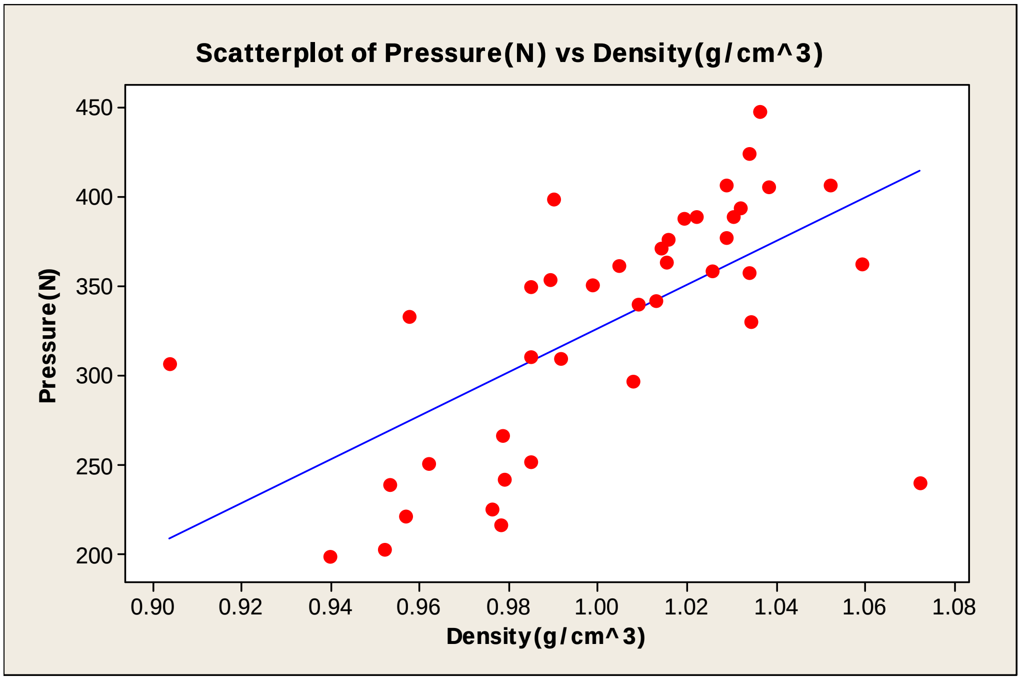

Figure 3.9 Scatter plot of Pressure (N) vs. Density (g/cm^3)

Pressure to density comparison from the failure test revealed a positive sloping graph indicating that if the density increases, the pressure required to deform the material would increase too.

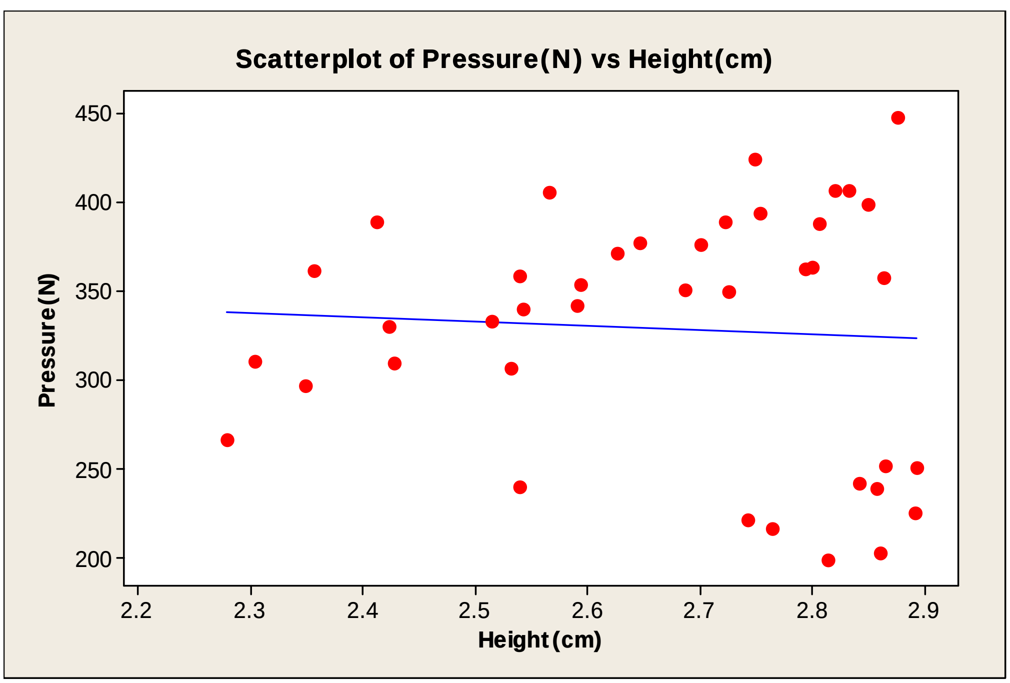

Figure 3.10 Scatter plot of Pressure (N) vs. Height (cm)

Pressure to height comparison from the failure test revealed a negative sloping graph indicating that if the height increases, the pressure required to deform the material would decrease. This is due to the fact that with increase in height results in increase in the number of weak spots and these made the briquettes crumble much faster than the shorter ones with less number of weak spots.

In spite of the success achieved with press method, a major challenge exists on the feasibility of its commercial viability. The current cost of manufacturing a custom made automated machine that would produce briquettes on a commercial basis far outweighs the benefit.

Extrusion Method

The extrusion method started with an attempt to design and manufacture a simulation model that would imitate the wood pellet manufacturing process.

Extrusion deals with the compaction of particles through a confined passage that is open at one end. If pressure is high enough, no binders may be required to produce briquettes. Natural components of the wood such as lignin have binding tendencies, which may be activated at high pressures to become binders.

At present, two main high pressure extrusion technologies exist: piston press and screw extrusion machines. They are used for briquette production as well. While the briquettes produced by a piston press are completely solid, screw press briquettes on the other hand have a concentric hole which gives better combustion characteristics due to a larger specific area[11]. Table 3.3 shows a briefly comparison of these two approach.

[11] BIOMASS BRIQUETTING:TECHNOLOGY AND PRACTICES, P.D. Grover & S.K. Mishra, 1996

Table 3.3 Comparison of a screw extruder and a piston press

	Piston press	Screw press
Optimum moisture content of raw material	10-15%	8-9%
Wear of contact parts	low in case of ram and die	high in case of screw
Output from the machine	in strokes	continuous
Maintenance	high	low
Combustion performance of briquettes	not so good	very good
Carbonization to charcoal	not possible	makes good charcoal
Suitability in gasifiers	not suitable	suitable
Homogeneity of briquettes	non-homogeneous	homogeneous

An investigation was carried out to locate possible mills where briquettes could be produced in large quantities. No screw extrusion briquette mill was in an accessible range, rather only an extrusion pellet mill was found in La Junta, so we developed a simulation model of the piston press to demonstrate the feasibility of mass production.

The Simulation model

In accordance with the principles of the piston press mechanism, the simulation model works in a discontinuous approach i.e., the material is fed through the hopper which is the taper and compressed into a one inch cylinder die by raising a five inch hydraulic base to a ram, which acts as a piston press procedure. Heat is applied simultaneously by an electrical coil heater fixed on the outer surface of the die, to raise the temperature to approximately 227.5°F. The electrical heater was thermostatically monitored at all times. This was done to simulate the real production conditions of a piston extrusion mill. As a result the lignin in the wood starts to flow and becomes a natural glue to bind the fly ash and sawdust. As the material comes out of the die, the lignin solidifies and forms cylindrical briquettes. The height of the briquette depends on the amount of feed and output amount each press. The whole experiment is conducted manually, while the actual piston press mill is driven either hydraulically or mechanically. Also, for a piston press, this experiment is reliable with proper installation of dies by means of circled fixation slot with the same center point.

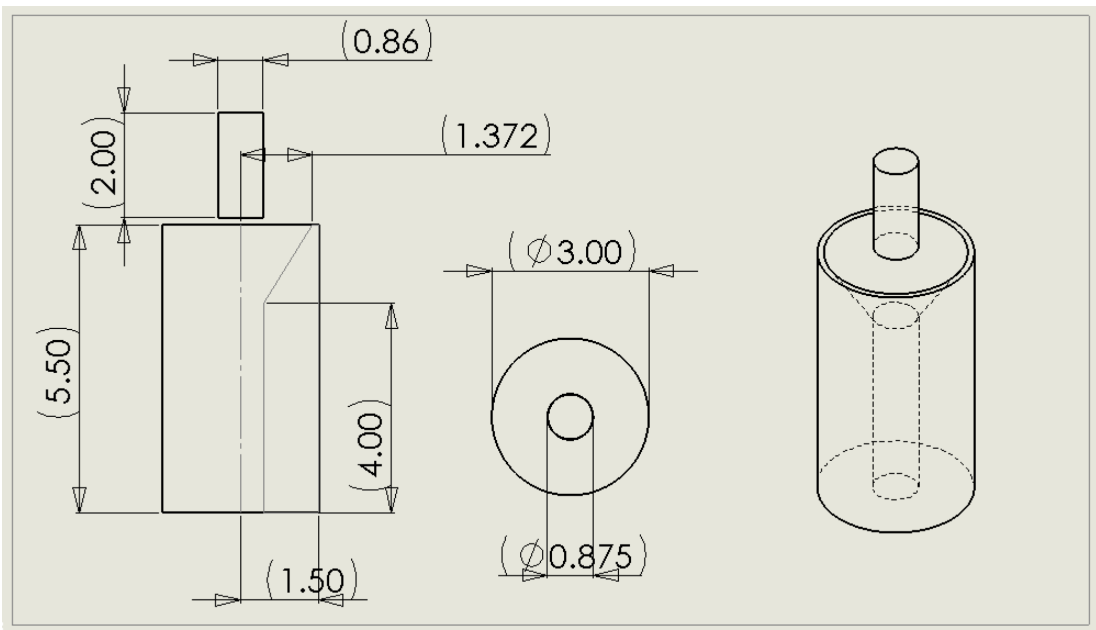

Figure 3.11 Schematic Drawing of Extrusion Model

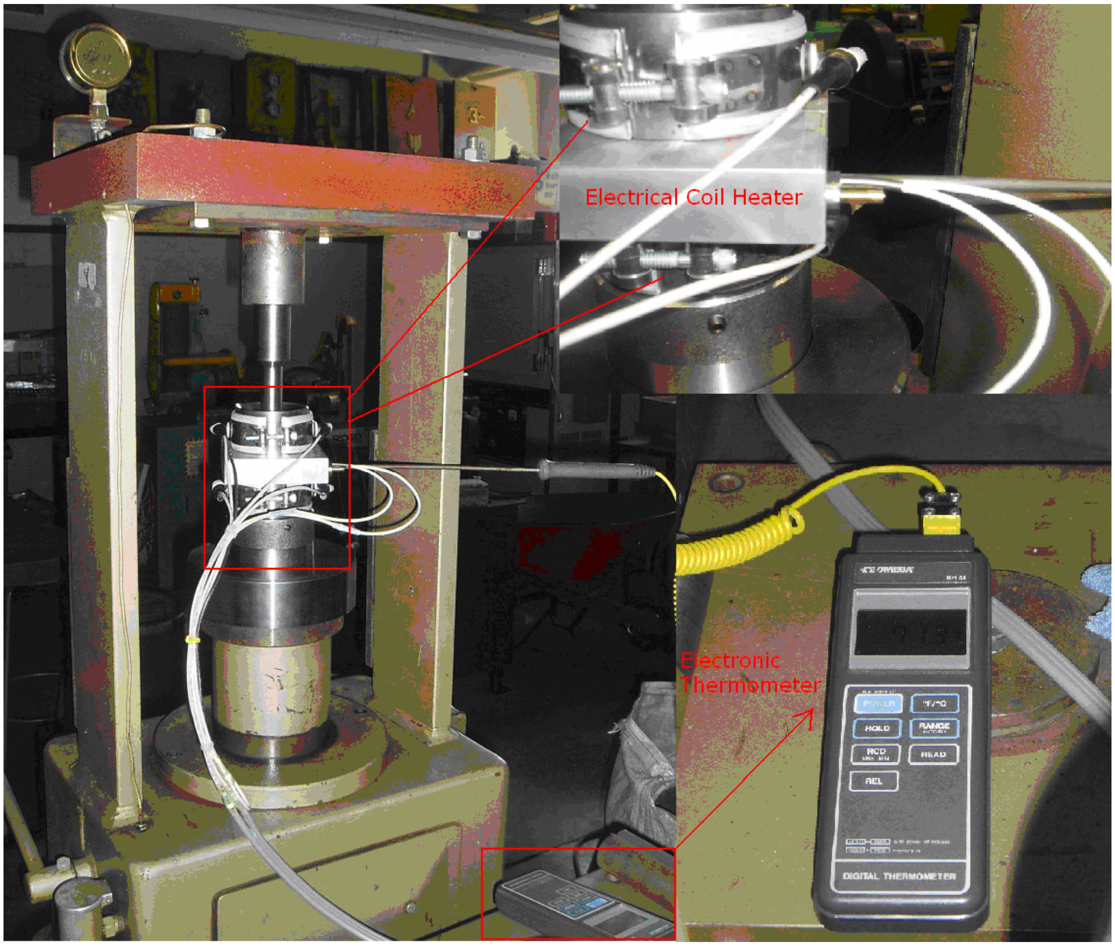

Figure 3.12 Extrusion Model

The pictures of the simulation model and the briquettes produced from it are shown below.

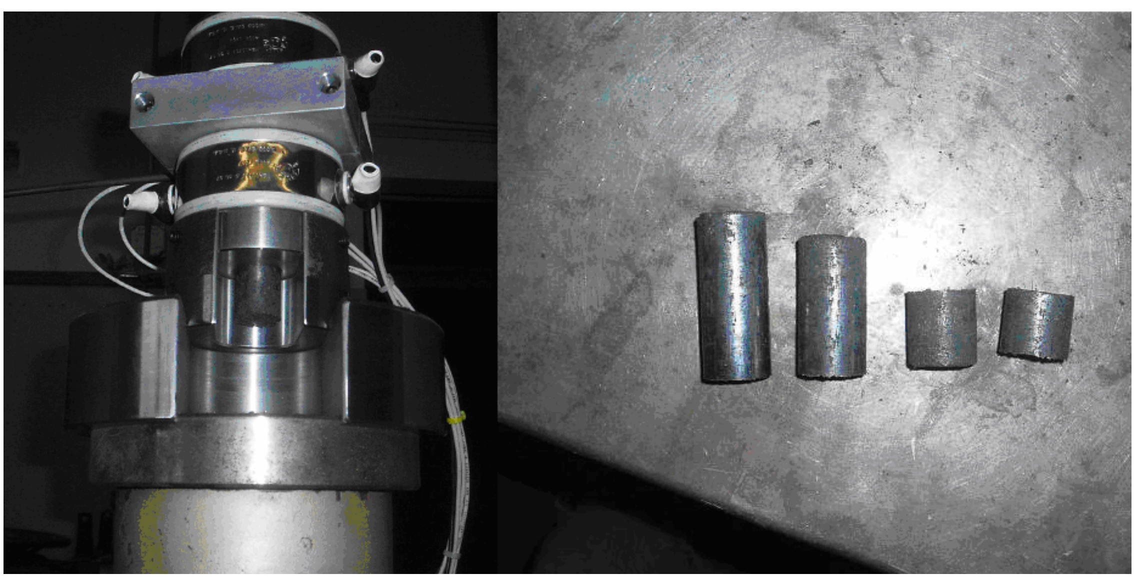

Figure 3.13 Briquettes produced by Extrusion Model

The briquettes produced by the extrusion model were impressive. They were well compacted, and strong. Eleven briquettes were produced and a failure test was conducted on them to determine their strength. The results are shown below.

Table 3.4 Strength Test Results for Extrusion Model

Pressure(N)	Height(cm)	Density(g/cm^3)
778.313	6.2	0.639449
792.545	5.99414	0.685992
841.467	5.91273	0.692687
819.23	5.7008	0.694595
801.44	5.60383	0.703193
794.324	5.6	0.708858
748.07	5.55817	0.709064
821.009	5.5	0.709639
748.514	5.44792	0.73112
819.23	5.40024	0.741023
810.335	5.3314	0.757665
799.049	5.3	0.758709
799.115	5.26411	0.761093
811.05	5.18289	0.762316
815.775	5.18036	0.767026
740.636	5.04113	0.767605
807.89	4.97075	0.777421
831.033	4.95398	0.78404
823.529	4.9	0.78941
793.755	4.8	0.794342
762.291	4.8	0.796036
788.894	4.78777	0.803516
840.815	4.78686	0.809131
756.882	4.71399	0.810735

	821.363	4.59762	0.81256
	838.784	4.4655	0.819766
	780.929	4.45077	0.839146
	797.253	4.42068	0.843649
	807.999	4.30067	0.846947
	860.979	4.3	0.851229
	763.327	4.22697	0.856232
	838.373	4.20433	0.859222
	803.173	4.2	0.859921
	781.021	4.2	0.881772
	864.998	4.15338	0.885295
	775.874	4.06563	0.903694
	834.256	4.02268	0.904452
	736.65	3.73859	0.906281
	822.724	3.59569	0.917429
	786.785	3.5	0.920595
Max.	864.998	6.2	0.920595
Min.	736.65	3.5	0.639449
Average	801.491975	4.8343395	0.796571375

After inputting above results into Minitab, the following graph can be obtained as well as the same conclusion we can get according to analysis of pressed briquettes.

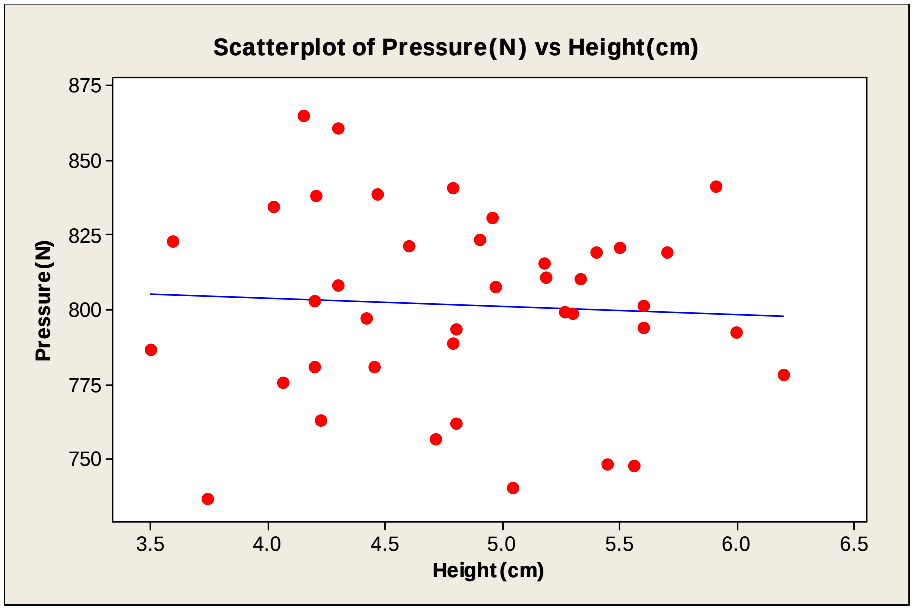

Figure 3.14 Scatter plot of Pressure (N) vs Height (cm)

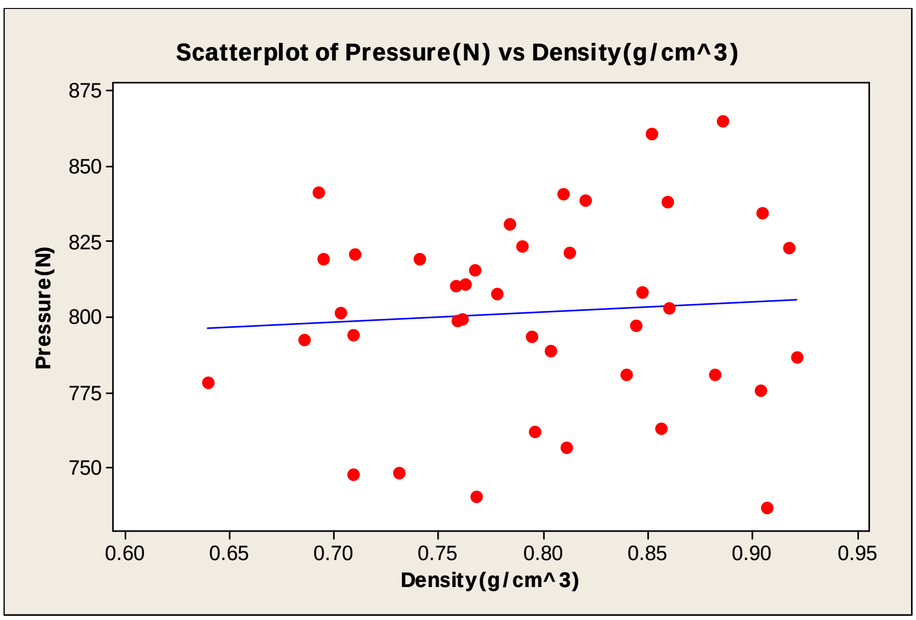

Figure 3.15 Scatter plot of Pressure (N) vs Density (g/cm^3)

Trial at La Junta Wood Pellet Mill

The extrusion process culminated in the trial run at the La Junta Saw mill on April 14, 2006. In order to carry out the trial run which required the production of two tons of wood/fly ash mixture i.e. 2400lbs of wood and 1200lbs of fly ash, the team purchased 3000lbs of wet sawdust from

Tom Mc Comb Lumber Company, Canon city. The sawdust had approximately 26% moisture content and it had to be dried to the desired moisture content which is anything below 6%. The drying process took approximately 7 weeks of constant drying on a daily basis using three clothes driers, two baking ovens and a green house owned by the department of Industrial and Systems Engineering. This was because there was no other suitable means readily available. The final amount of the total dry wood is 2182lbs. Equipments and facilities mentioned before can be seen as below.

Figure 3.16: Facilities Used to Dry Saw Dust

The process at the Tom Mc Comb Lumber Company, Canon city involves first grinding the saw dust into finer particles using the hammer mill. Afterwards the material is mixed properly in the required ratio and fed into a die that has several orifices. The die at the saw mill consists of smooth straight sided holes whose diameters are 1.25" at the inlet and 0.875" at the outlet. A roller revolves over the mixture at the inlet of the die as the die is fed in. Briquettes of dense material thus form and are cut by a knife that rotates under the die.

On the first run, the coal/fly ash mixture didn't extrude rather, we observed some smoke emanating from the extrusion chamber after several minutes of running the mill. The process was stopped immediately and the chamber was opened. Immediately it was opened, explosions started occurring but stopped after a while. On cleaning the die, the process was repeated a second time with some moisture injected into the system simultaneously, the coal/fly ash mixture didn't extrude this time either. At this juncture, it became obvious that the mixture would not come out. Some of the pictures are seen below:

Figure 3.17: External View of the Die after Removing the Cover

Figure 3.18: Internal View of the Die and Rollers

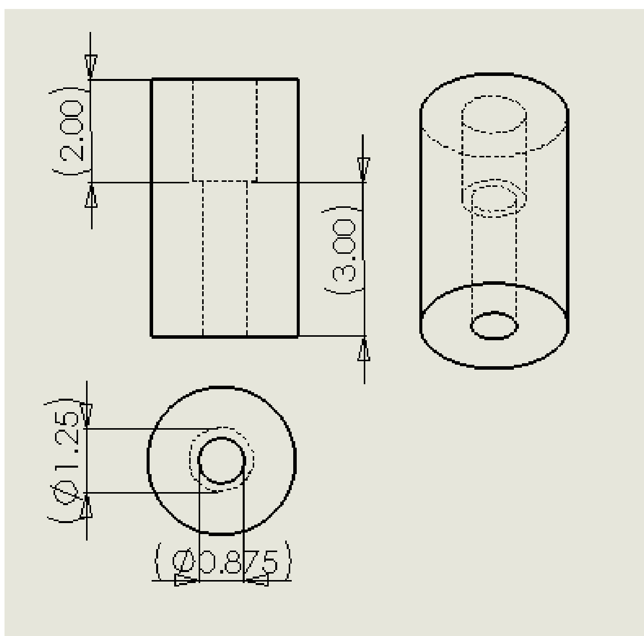

Figure 3.19: Schematic Drawing of the Certain Hole on the Die

Figure 3.20: Briquettes Produced from the First Run in La Junta

Analysis of trial run at La Junta Wood Pellet Mill

1. The main reason for the failure of the trial run is the shape of the die. The die at the saw mill consists of smooth straight sided holes whose diameters are 1.25” at the inlet and 0.875” at the outlet. The purpose of the larger diameter at the inlet is to start a steady flow of the wood/flyash mixture into the die. As the roller revolves, it forces the mixture into the die and compresses it in the process. However, by the time the mixture gets to the constriction which caused by the difference in diameters, the briquettes would have formed and are too hard to pass through. This resistance to the extrusion occurs because the holes are not tapered and the constriction is not smooth enough to permit unrestricted passage of the briquettes. The pictures and a schematic diagram are shown below.

Worthy of note is the fact that the conventional extrusion process is designed mostly for production of briquettes from cattle feed (oat, wheat, corn, alpha-alpha, etc.) and wood which are not as strong as we require for briquettes. These materials are much softer and less abrasive than the materials we used for briquettes (fly ash and saw dust). These differences did not help to our extrusion trial in La Junta. So we recommend the use of a straight holed die instead of a tapered die, which also means that pressure would be applied in single dimension rather than 3 dimensions thereby reducing the force applied on the material at each time.

2. The moisture content required for a conventional briquetting process ranges from 10-12%. However, the results of our press and extrusion simulated models showed that only moisture content less than 6% was acceptable thus leading us to use that moisture content. This reduced moisture which we used may have led to the production of hard briquettes much faster than mixtures with more moisture would, and the wood/fly ash mixture would have been more compressible at the critical point.

3. Heat produced during the extrusion process was so much that it led to faster vaporization of the moisture and the eventual burning of the mixture. This was obvious with the smoke that emanated from the die and the subsequent explosions that occurred when it was opened.

Economic Analysis

An economic analysis of the savings in monetary terms for Aquila should they decide to use the wood/fly ash briquettes to replace some coal is shown below.

Energy Savings:

Total fuel burned per day	500 tons (coal)

BTU/lb of coal 11000

Note: BTU/lb of dry wood is about 9100 to 9400. BTU/lb of fly ash is about 5912.

BTU/lb of briquettes should be about 0.6 * 9250 + 0.4 * 5912 = 7914.8 since 60% of the briquettes are dry wood. BTU content test of wood-Fly ash mixture is obtained from Aquila Lab as follow:

Table 3.5 Test Results of BTU Content from Aquila Lab

BTU Content	Old Result	New Result
Received	8372	8309
Dry Sample	8501	8482

BTU/lb of briquettes (8372+8309)/2=8340.5

Aim: To replace some of the coal burned per day with briquettes we produced.

Let RR be the Replacement Ratio of coal with briquettes. Then RR=11000 / 8340.5= 1.318866. Assume we replace X tons of 500 tons coal with briquettes. In order to have the same total energy, we must replace X tons of coal with RR*X tons of briquettes.

Restrictions:

Mass of wood burned per day cannot exceed 5% of total mass of fuel burned per day.

500 - X + RR*X = 500 + (RR-1)*X is the total mass of fuel that will be burned per day. Mass of wood that will be burned per day is 0.6*RR*X tons.

$0.6*RR*X \leq 0.05 * (500 + (RR-1)*X)$,

$(0.55*RR + 0.05) * X \leq 25$,

$X \leq 25 / (0.55*RR + 0.05) = 32.242$.

X (≤32.242) tons of coal can be replaced with RR*X (≤42.523) tons of briquettes a day.

Let's make X the maximum possible value (≈32.242). Then we'll need 0.4*RR*X = 17.01 tons of fly ash every day. We already have much more fly ash than we need (more than 35 tons a day).

Savings:

500 tons of coal produces 70 tons of ash a day. Assume that briquettes produce useless ash of 30% of their total mass (%40 of briquettes are fly ash, and fly ash has %40 usable carbon in it, that is, fly ash has %60 useless ash in it. So, at least %40 * %60 = %24 of briquettes are useless ash. Wood produces very small percentage of ash).

- Ash produced by coal reduces by X * 70 / 500 = 4.514 tons a day due to less usage of coal by X tons.
- Briquettes produce 0.3*RR*X = 12.757 tons of useless ash a day.
- Ash produced by coal reduces by 0.4*RR*X = 17.01 tons a day due to usage of fly ash in the briquette production.

So the amount of waste dumped to landfill reduces by 17.054 + 4.341 - 12.791 = 8.766 tons a day. Savings: 8.766 tons/day * $8.6/ton = $75.391/day.

From fuel costs, X tons/day * $32/ton = $1031.757/day will be saved.

Assuming 365 days a year, 365 * ($1031.757 + $75.391) = $404,109.11/year will be saved.

Chapter 4

Conclusion and Recommendation

Conclusion

Using the closed chamber prototype we have demonstrated that producing briquettes from just fly ash and dry saw dust only is possible at high pressures. Through the extrusion prototype we have demonstrated that closed chamber is not a strict requirement, and a well-known and similar method can be used as well. Moreover briquette production out of fly ash and dry saw dust is possible without a binder, conforming to our requirement of not getting a new permit for the Aquila plant. In addition, it is a profitable venture due to the savings from the cost of dumping fly ash into the landfill, and the reduction of the amount of coal needed to burn since some of the coal can be replaced by the briquettes.

Due to the huge success of the extrusion trial at our lab, we had good expectations from the piston extrusion process in La Junta. The piston extrusion did not work because of the shape of the holes in the dies, and the heat produced in the process due to the high speed rollers. Also the piston process was designed to work with cattle feed (oat, wheat, corn, alpha-alpha, etc.) and wood (which is not as dry as we require for briquettes) **with** binder. These materials are much softer and less abrasive than our materials for briquettes (fly ash and saw dust). These differences did not help to our extrusion trial in La Junta.

Overall this project was a huge step towards realizing commercial briquette production. We have delivered an ideal ratio for the saw dust and fly ash mixture, designed two working prototype processes (closed chamber press and extrusion) -capable of producing good (strong, high btu) briquettes- that can be extended and automated to produce briquettes in an industrial way.

Recommendation for Future Work

We recommend that further work be done on the extrusion method because it appears to be the most feasible possibility currently. The following factors should be explored with this process. They are:

The shape of the die:

The current shape of the die is a huge barrier. It is straight all through the die except for where the constriction occurs. So the possibility of an extrusion process that uses a tapered die should be explored.

Moisture content:

The percentage of moisture in the feed biomass to extruder machine is a very critical factor. In general, it has been found that when the feed moisture content is 8-10 %, the briquettes will have 6-8% moisture. At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. But when the moisture content is more than 10%, the briquettes are poor and weak and the briquetting operation is erratic.

References

1. [1] Alternatives Assessment to Determine Effective Re-use of Fly ash, Bottom Ash and Coal Dust From Canon City Power Plant, CABJ Engineering Consultants, 2004.
2. Aquila Narrative, Colorado State University-Pueblo, 2005.
3. http://www.state.co.us/oemc/programs/waste/forest_thinnings/canoncity.htm
4. http://geoinfo.nmt.edu/labs/microprobe/description/sem.html
5. http://oregonstate.edu/trees/con/spp/pinespp.html
6. http://www.wwpa.org/ppine.htm
7. http://www.biocrawler.com/encyclopedia/Lignin
8. http://www.lignin.org/
9. http://www.rpi.edu/dept/chem-eng/Biotech-Environ/FUNDAMNT/lignin.htm
10. http://thunder1.cudenver.edu/chemistry/classes/LabNet/bomb/theory.html
11. Biomass Briquetting: Technology and Practices, P.D. Grover & S.K. Mishra, 1996
12. Malhotra, Ravi, Alternatives Assessment to Determine Effective Re-use of Fly ash, Bottom Ash and Coal Dust From Canon City Power Plant, *CABJ Engineering Consultants*,2004.
13. Aquila Narrative, *Colorado State University-Pueblo,* 2005.
14. http://www.state.co.us/oemc/programs/waste/forest_thinnings/canoncity.htm
15. http://www.tfhrc.gov/hnr20/recycle/waste/cfa51.htm
16. http://www.wwpa.org/ppine.htm
17. http://thunder1.cudenver.edu/chemistry/classes/LabNet/bomb/theory.html
18. Grover, P.D & Mishra, S.K, Biomass Briquetting: Technology and Practices, 1996